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Hydrological Influences on Catahoula Lake in an Altered Floodplain

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HYDROLOGICAL INFLUENCES ON CATAHOULA LAKE IN AN ALTERED FLOODPLAIN

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ABSTRACT

Floodplain lakes in floodplains of large rivers undergoing intensive alterations are subject to hydrologic alteration. One example is in the Lower Mississippi Alluvial Valley (LMAV) and pivotal habitat for wildlife. Catahoula Lake has experienced hydrologic regime alterations over the past ~150 years that may be contribute to changes in the habitat with expansion of woody plants. A Diversion Channel was constructed in 1972 to provide the natural, annual de-watering of the lake to maintain its ecological integrity, but ecologic changes are still occurring. Our general goal is to understand the hydrologic regime of the lake, particularly the historical hydrologic regime of Catahoula Lake and to identify the contribution of the adjacent rivers – Little, Atchafalaya, Red, Black, Ouachita, Tensas, and Mississippi rivers – to the variability of Catahoula Lake prior to and after extensive hydrologic modifications in the LMAV. Historical lake level and neighboring rivers stage time series were used to estimate the hydrologic links between the lake and its surrounding rivers. Our analyses were done for three time periods: (1) immediately prior to the Diversion Channel construction, (2) post-Diversion Channel period, and (3) estimated condition in the late 1800s prior to incision of the Atchafalaya River. Results indicate that water levels on the lake are complexly related to the influxes of the Little River or the stage of the Black River stage at Jonesville, and the most consistent relationship is with the Atchafalaya River, which controls the lake level via a backwater effect at stage 7.3 m or higher. This backwater effect has been reduced from 207 to 120 days per year between 1880 and 2010. Compared to its condition prior to hydrologic alterations, results indicate modifications in the LMAV and the construction of the Diversion Channel have altered the lake regime. Our best estimates is that current lake levels are lower in the high-water spring, less variable in the dry period, and lack the extreme high water events of 100+ years ago.

INTRODUCTION

Floodplains are one of the most important ecosystems and serve for a multitude of resources (Kummu et al. 2014), and they have undergone extensive anthropogenic manipulations (Hudson 2006). Sparks (1995) found that floodplains support important biodiversity but are liable to alterations due to hydrologic modifications and management. The Mississippi River system includes a large floodplain, which has experienced many changes due to the hydrologic modification for navigation, flood control, and other local river structure managements (Pinter et al. 2008).

Floodplain lakes are important elements of floodplains of large rivers (Mertes et al. 1996, Hudson 2006).Catahoula Lake, in central Louisiana in the Lower Mississippi Alluvial Valley (LMAV), is both one of the largest floodplain lakes and one of the most ecologically important waterfowl habitats in the LMAV. Catahoula Lake is a rim-swamp lake (Brown 1943), impounded to the north by an abandoned channel of the Arkansas River, to the south and east by a sequence of older alluvial ridges, and to the west by Tertiary uplands (Saucier 1967). This lake has a complex geologic and hydrologic history and its water level fluctuates nearly more than 6 m annually. Its watershed is 6,215.9 km^2, and the lake covers approximately 120 km^2 (Willis 2009). Catahoula Lake is covered with a variety of vegetation communities, and is important habitat for large numbers of migratory birds (Lotz 2000) (Fig. 1).

Lakes are formed in a variety of ways, depending on their geographic location and the geological and biological forces at work within that region (Cech 2010). A backswamp lake is a type of floodplain not covered with woody vegetation, and processes that form this kind of lake are not common in the LMAV. Tonle Sap lake of Cambodia in the floodplain of Mekong River and Lake Lago Grande de Curuaí in the floodplain of the Amazon River in Brazil as well as

Calado lake in central Amazon basin are typical examples of floodplain lakes that experience unusually large annual fluctuation (Lesack and Melack 1995, Bonnet et al. 2008, Kummu et al. 2000, kummu 2014). The main variables responsible for that fluctuation are backwater flow, overland exchanges with the floodplain, headwater flow, and rainfall. However, the hydrologic processes responsible for the unusually large annual fluctuation and that maintain the important vegetation communities of Catahoula Lake are not well understood.

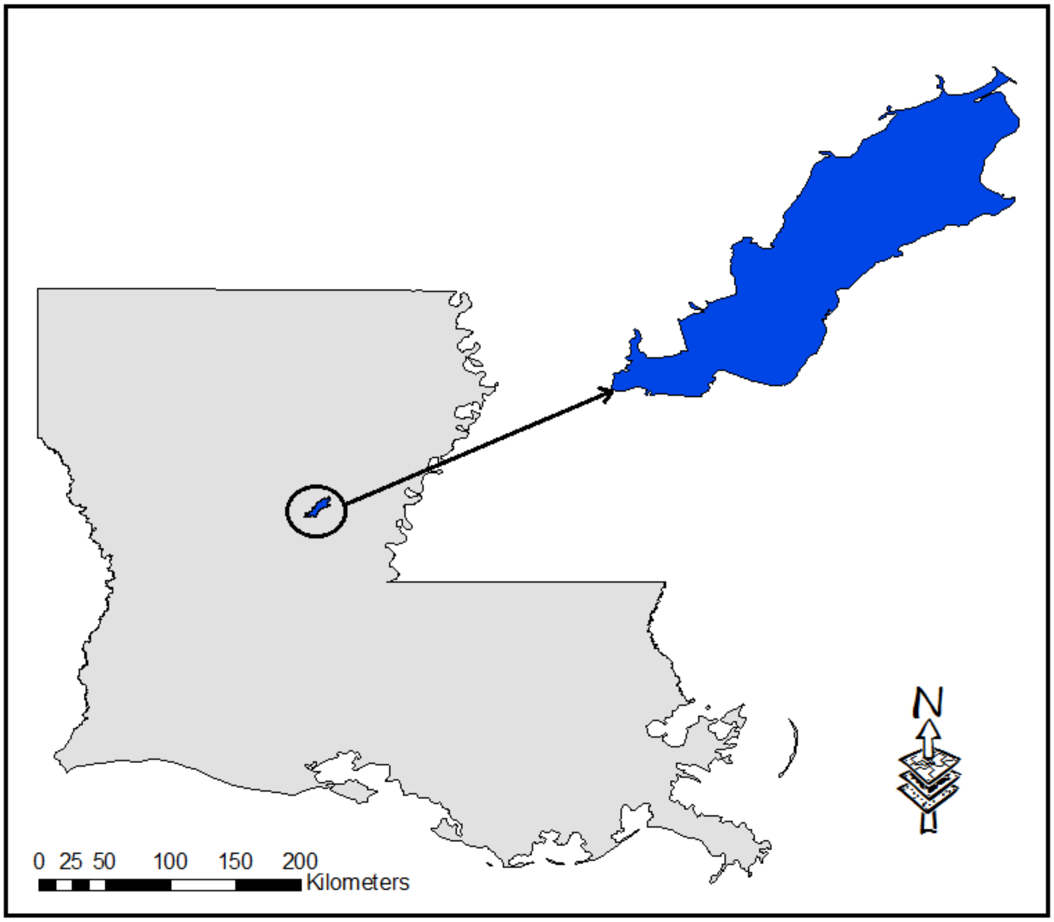


Figure 1. Location of Catahoula Lake in Louisiana, USA.

Wills (1963) described the hydrology of Catahoula Lake as unusual and seasonal because water depth and flooding frequency vary from year to year. Usually, the lake stage begins rising in the late November -early December, with a sharp water level increasing in January, and the lake level remains high until June. The lake level begins receding in July, and about early August until October, the lake drains to expose most of the bed with a relatively shallow pool of about 8 km^2 (Brown 1943, Willis 2009).

Lower Mississippi Alluvial Valley (LMAV)

The deposition of sediments brought by the Mississippi River formed the Lower Mississippi Alluvial Valley. Throughout the Pleistocene, the LMAV was incised and alluviation occurred during the Holocene (Tye and Coleman 1989). Broad areas of approximately flat land near sea level have been created in the non-deltaic valley (Kolb and Van Lopik 1958).

In the LMAV, backswamps are depressions, often in river meanders (Tye and Coleman 1989). Natural levees formed of coarse deposited materials constitute ridges, while low-lying backswamps with fine-grained sediments form away from channels (Fisk 1944, 1947; Frazier 1967; Tye and Coleman 1989). Generally, the backswamps are flooded each spring under natural conditions (Brody et al. 1989). Flooding can be from river water or a mixture with rainfall and runoff from nearby uplands or local floodplain sources (Mertes 1997).

Lower Mississippi Alluvial Valley (LMAV) Hydrologic Modifications

The hydrology of Catahoula Lake is related to its position in the LMAV. According to Biedenharn and Watson (1997) the LMAV has a width that varies from 48 to 200 km and has been historically subjected to flooding during periods of peak flows, so the Mississippi River, as the chief river in the LMAV, influences all nearby water bodies and is one of the most regulated and studied rivers throughout the world (Hudson et al. 2008). Over the past century, many engineering and maintenance projects implemented on the Mississippi River – such as navigation projects and water control structures as part of the Mississippi River and Tributaries (MR&T) Project, and many other adjustments in the Mississippi and Red rivers – have altered its morphology (Remo et al. 2009) and may be in turn modifying the hydrology of Catahoula Lake (Fig. 2). The flood of 1927 is considered as the genesis of the MR&T project, which was authorized by the Flood Control Act of 1928 and was the first comprehensive flood control and navigation act in the U.S., and the period 1933-1942 was a period of meander cut-offs in which the most changes were made in the river (Biedenharn and Watson 1997).

Of particular importance have been changes in the LMAV at the confluence of the Mississippi and Red rivers. Brown (1943) realized that stages of Catahoula Lake are linked to Black River stages, which in turn are linked to stages of the Red and Mississippi rivers via a backwater effect. This link has been changing over time with management. Before 1858, the Atchafalaya River contained a log raft that prevented Mississippi River water from routing via the Atchafalaya River, and after removing this raft, increased water flow from the Mississippi River tended to flood the Atchafalaya River and created gradual incision of this river (Reuss 2004, Mossa 2013). The Old River Control Structure (ORCS) was built in 1963 to manage the amount of water that flows from the Mississippi River to the Atchafalaya River. This structure prevents the entire Mississippi River flow from entering the Atchafalaya River, but has not prevented further incision. Thereafter, the incision of the Atchafalaya River has caused a continuous downward change in the water levels of Black River (Willis 2009).

Little River Watershed

Formed by the confluence of Dudgemona River and Castor Creek near Rochelle, the Little River is the main drainage area into Catahoula Lake from the Tertiary uplands west of the lake. The Little River basin area accounts for nearly the entire 6,215 km^2 watershed feeding Catahoula Lake and its annual precipitation is about 1,470 mm (Gaydos et al. 1973; Latuso 2014).The highest point within the basin is 163 m, which is the highest point in the state. The watershed is composed of rounded hills in the north, flat-lying deposits in the central and dissected terrace deposits in the south.

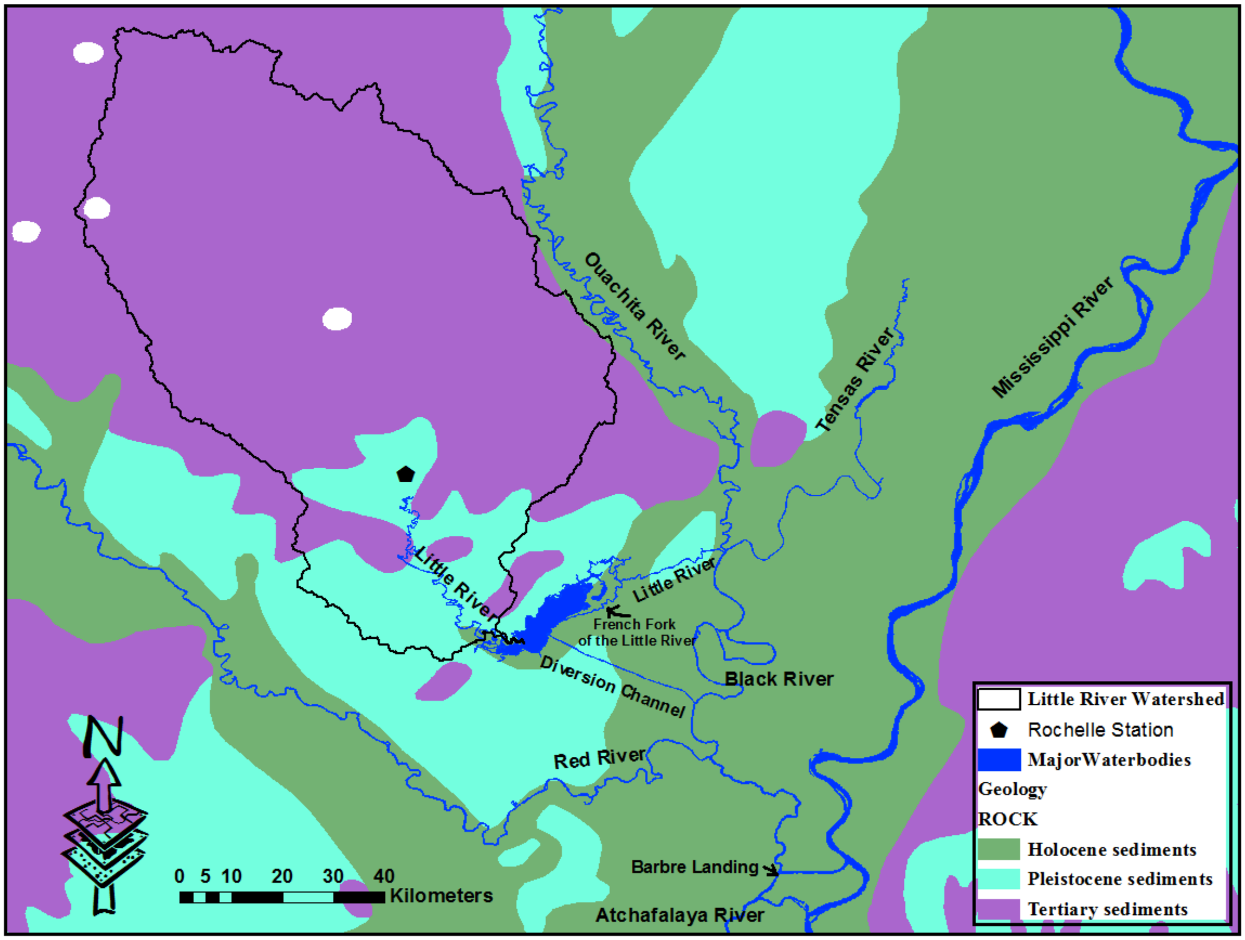


Figure 2. Catahoula Lake and its surrounding waterways: the Little River watershed, Red, Atchafalaya, Tensas, Ouachita, Black, and Mississippi rivers, and the Diversion Channel.

Black River

Because the fluctuation of Catahoula Lake water stage depends on the neighboring rivers as identified by Brown (1943) and Bruser (1995), it is relevant to quantify the hydrologic influence of the Mississippi and Red rivers on Catahoula Lake. Black River is formed from a convergence of the Tensas and Ouachita rivers at Jonesville. The Black River flows into the Red River about 70 km south of Jonesville (USACE 2014). As part the Ouachita-Black Rivers

Navigation Project, the first hydrologic modifications of the Ouachita and Black rivers were made, beginning in 1902 and completed in 1924, as a 542-km long waterway was constructed to allow navigation from Camden, Arkansas to Jonesville, Louisiana. In 1926 and 1972, a number of locks and dams were built on the Black River to enable navigation (USACE 1998). As a result of the 1972 locks and dams, the minimum water stages within Black River would have been raised and created permanent flooding of Catahoula Lake (Sessums 1954). Therefore, although the lake drained through the French Fork of Little River prior to hydrologic modifications, the Catahoula Diversion Channel was constructed to allow drainage to bypass the locks and dams on the Black River.

Ouachita and Tensas rivers

The Ouachita River originates from the Ouachita basin in both Arkansas and Louisiana, and has been subject to construction of dams and locks, and clearing of channels for navigation since 1871. The Jonesville project consisting the improvement of levees, floodwalls, two surface drainage structures, a storm sewer, a storm drainage pumping plant, and an outlet ditch that aimed to prevent flooding problem due to the headwater floods on the Ouachita-Black rivers and backwater effects of the Red and Mississippi rivers was completed in 1952, while locks and dams for navigation were completed in 1972

Red River

The Red River is a major tributary of the Mississippi River (Saucier 1967) that flows from the northwest to join the Atchafalaya River at the Old River structure, and receives water from the Black River about 70 km below the head of the Black River (USACE 2014). The capture of the Red River by the Atchafalaya played a pivotal function in the Mississippi-

Atchafalaya diversion and in the Atchafalaya River flux by maintaining sediment transport and seasonal low water flow.

Catahoula Lake Hydrology

The approximately flat-bottomed lake has oscillating water stages from 2.78 to 6 m per annum. When neighboring river water levels are low during summer, there is shrinkage of the lake surface from about 120 km^2 to about 20 km^2, and Willis (2009) observed water depth of the permanent pool at the middle of the lake of 2.5 to 30 cm.

Bruser (1995) concluded that neighboring rivers may affect the lake drastically when they are at high water levels and prevent drainage from the lake. The complicated hydrological alterations in the region are therefore likely to have modified the hydrological regime of Catahoula Lake. Although the Red, Tensas, Atchafalaya, and Black rivers may also have hydrologic influences on Catahoula Lake, the most important rivers that directly impact Catahoula Lake are probably the Little and Atchafalaya rivers. The Little River watershed drains all of its water into Catahoula Lake, and its watershed is the principal headwater inflow of the lake. The incision of the upper Atchafalaya is correlated with lowering of water levels in the Black River (Willis 2009).

Catahoula Diversion Channel

Through the Catahoula Diversion Channel, the lake water level is managed following a compromise among LDWF, U.S. Fish and Wildlife Service (FWS), and the U.S. Army Corps of Engineers (USACE) (Bruser 1995; Joshi 2012), with the goal to mimic the pre-modification hydrologic variability and thus maintain ecosystem services. Today, the hydrologic regime of the lake is managed through the Diversion channel and a check dam on the Little River near Archie.

The management plan is to maintain the level of water in the lake from November to January at about 8.84 m, increase stage to about 10.36 m until July, and to dewater the lake to the 2.5 meter minimum from July to November. However, there are some variations in response to weather events and water levels in adjacent rivers.

Vegetation communities

The vegetation in the lake is arranged into zones according to the water depth, flooding duration, and hydrologic regime (Brown 1943; Wills 1965; Bruser 1995). Vegetation bands, from mixed hardwood, baldcypress, water elm (*Planera aquatica),* swamp privet (*Forestiera acuminata*), dwarf shrubs, and, finally, grasses are found in the area surrounding the lake toward the center of the lake. Close to the escarpment, mixed hardwoods, consisting of sweet gum *(Liquidambar styracflua),* water oak *(Quercus nigra),* cherrybark oak *(Q. pagoda),* deciduous holly *(Ilex decidua),* chittumwood *(Bumelia sp.),* persimmon *(Diospyros virginiana),* red haw *(Crataegus sp.),* and baldcypress *(Taxodium distichum),* are found. During the summer, the ground is covered by grasses and herbs such as the six-week fescue *(Festuca octoflora)* and pink sensitive plant *(Mimosa strigillosa).* In the late fall, Bermuda grass *(Cynodon dactylon),* carpet grass *(Axonopus compressus), Fimbristylis* sp., and spike rushes *(Eleocharis* sp.*)* are found. Bruser (1995) found there are also water tupelo (*Nyssa aquatica*) and water locust (*Gleditsia aquatica*), which are tolerant to water, on the perimeter of the lake. Inside the ring of woody plants, there are many herbaceous plants such as chufa (*Cyperus esculantus*), sprangletop (*Leptochloa fascicularis*), wild millet (*Echinochloa walteri*), teal grass (*Eragrostis hypnoides*), and duck potato (*Saggitaria latifolia*). The herbaceous plants are important food for winter waterfowl.

Catahoula Lake Changes

Willis (2009) observed that anthropogenic shifts in the LMAV have caused important hydrologic modifications in Catahoula Lake. According to Bruser (1995), the construction of the Catahoula Diversion Channel increased lake drainage rates, and that therefore decreased water stage variations from August to November. Apparently, alteration of vegetation communities are related to hydrological shift in a floodplain ecosystem, and Joshi (2012) and Latuso (2014) found that herbaceous vegetation is being replaced by woody trees expanding in the lakebed.

These changes in lake vegetation have accelerated since the completion of the Catahoula Diversion Channel, and this change is likely related to the lake hydrology (Joshi 2012, Latuso 2014). Management of this structure may not be completely mimicking the natural hydrologic regime of the lake.

In short, the hydrologic regime of Catahoula Lake needs to be clearly understood to manage the lake according to its natural variability. An important motivation is the desire to develop methods for management of the water control structure on the Catahoula Diversion Channel.

OBJECTIVES

The objective of this research is to describe the historical hydrologic regime of Catahoula Lake, so that we can (1) identify the contributions of the adjacent Little, Atchafalaya, and Mississippi rivers on the hydrological regime in Catahoula Lake prior to and after extensive hydrologic modifications in the Lower Mississippi Alluvial Valley (LMAV), and (2) provide the basis for new water management to restore the hydrologic regime of the lake.

The specific objectives are to quantify hydrologic influences of neighboring water bodies:

1. Use historic stage data on the Little and Atchafalaya rivers to estimate their hydrologic influence on Catahoula Lake;
2. To estimate relative hydrologic effect on Catahoula Lake for the periods pre- and post-Catahoula Diversion Channel construction.

METHODS

To identify the hydrologic influence of the neighboring rivers on the lake regime, we selected the 1960s period because it is only the period with good data for the lake and adjacent rivers, and when the Catahoula-Black-Red-Atchafalaya connection was not yet completely interrupted by locks and dams even though a smaller series of locks and dams had existed since 1926. The Atchafalaya River stage time series at Babre Landing gauge presents a complete dataset for this time period, and by its strategic location is used to estimate the influence of the river on the lake (Fig. 2). This gauge location allows estimating the backwater effects of both the Mississippi and Atchafalaya (Red) rivers on the lake.

Conceptual Model

We set up a conceptual model of the lake that identifies possible hydrologic links between Catahoula Lake and its surrounding rivers (Fig. 3). We developed simple relationships based on simple hydraulic assumptions to structure and parameterize this model (Fig. 4).

We investigated the contribution of water influxes from the Little River watershed to the lake. There is no gauge at the outlet of the Little River at the lake, so we obtained discharge data from Rochelle station (USGS 07372200) to estimate the amount of water that the river generates to the lake. Rochelle station consists of a complete set of discharge for the period 1957-1991. The total area of the Little River watershed at Rochelle station is 4,929 km^2, which amounts to 75% of the total area of the entire watershed feeding Catahoula Lake. Therefore, we estimated total inflow to Catahoula Lake as:

$$\frac{\mathrm{WSA_T}}{\mathrm{WSA_R}} \times \mathrm{Q_{Ri}} = \mathrm{Q_{Ti}}\ , \qquad (1)$$

where WSA_T is the entire watershed surface area of Little River watershed including the lake itself and small watershed surrounding the lake (km^2), WSA_R is the drainage area of the Little River watershed at Rochelle station (km^2), Q_{Ri} is the discharge flow at Rochelle (cms), and Q_{Ti} is the total daily discharge flow that drains to Catahoula Lake (cms).

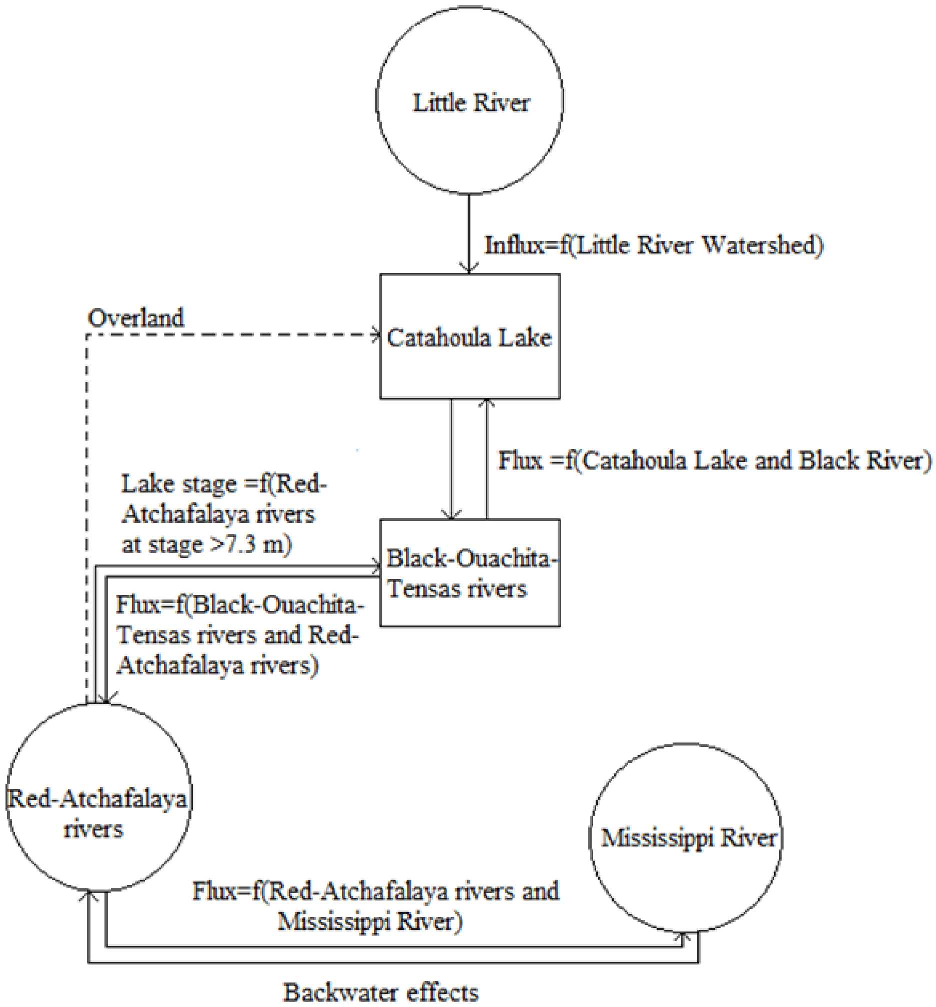


Figure 3. Conceptual model of Catahoula Lake and its interrelationships with the Little River watershed and the Red, Atchafalaya, Tensas, Ouachita, Black, and Mississippi rivers.

Considering the lake total area to be 120 km^2, we converted the runoff of the Little River watershed in flow (m/s) per second and then in loading rate per day (m/day) as:

$$\mathrm{IF_i} = \frac{\mathrm{Q_{Ti}}}{\mathrm{A}}, \tag{2}$$

where $\mathrm{IF_i}$ is the daily loading rate (m) of the Little River watershed to the lake, $\mathrm{Q_{Ti}}$ (eq. 1) is the daily total discharge (cmd) of the Little River watershed into the lake, and A is the total area (km^2) of the lake.

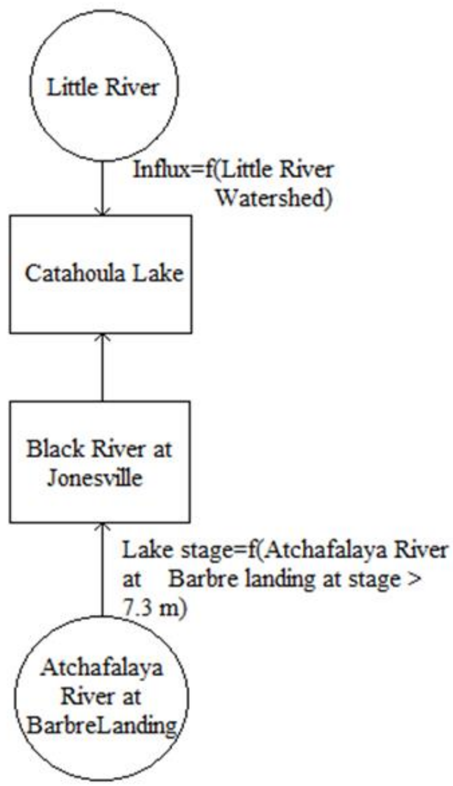


Figure 4. Simplified model of Catahoula Lake and its hydrologic interaction with the Little, Black, and Atchafalaya rivers.

We quantified the stage variation of the lake on a daily basis by subtracting lake stage the day after from lake stage the day before based on the Placid Oil Co. gauge data:

$$\Delta S_i = CL_i - CL_{i-i} , \tag{3}$$

where ΔS_i the daily lake storage in depth (m) is, CL_{i-1} is the lake water stage (m) of the preceding day, and CL_i is the lake water stage (m) for the day in which the lake storage is computed.

We investigated the total amount of water draining to the Black River as the daily net outflow (OF_i) of the lake, which is a difference of the total daily influx (IF_i) (eq. 2) and daily change in water storage (ΔS_i) (eq. 3), in terms of stage:

$$\Delta S_i = IF_i - OF_i , \tag{4}$$

The outflow (OF_i) is the amount of water that flows out of the lake, and is the difference between inflow and change in storage. This flow out is the amount of water that the lake does not have capacity to retain, and is expected to be related to the downstream gradient. This variable represents the net outflow of the lake after accounting for influx from the Little River, so it is a useful response variable to investigate the control of lake drainage by nearby downstream conditions.

We estimated the hydrologic influences of Red, Atchafalaya, and Mississippi rivers on the lake regime using data from Atchafalaya River at Barbre Landing, LA (USACE 03015) gauge established in 1880 (Fig. 2). We chose this gauge because it is at the junction of the Red, Atchafalaya, and Mississippi rivers, which control the hydraulic behavior of the region (Willis 2009). We therefore obtained the difference in water stage between the Atchafalaya River at Barbre Landing and the lake as a gradient (∇_I), computed on a daily basis for the study period.

$$\nabla_i = \begin{cases} CL_i - BL_i\,, BL_i > 7.3\ m \\ CL_i - 7.3\ ,\ BL_i < 7.3m \end{cases}, \tag{5}$$

where CL_i is the daily lake stage (m), BL_i is the daily Atchafalaya River stage (m) at Barbre Landing. The threshold of 7.3 m is the elevation of the bottom of the lake. Below this elevation, the outflow from the lake is not controlled by backwater and the lake is essentially impounded at its low-water pool (Fig. 5).

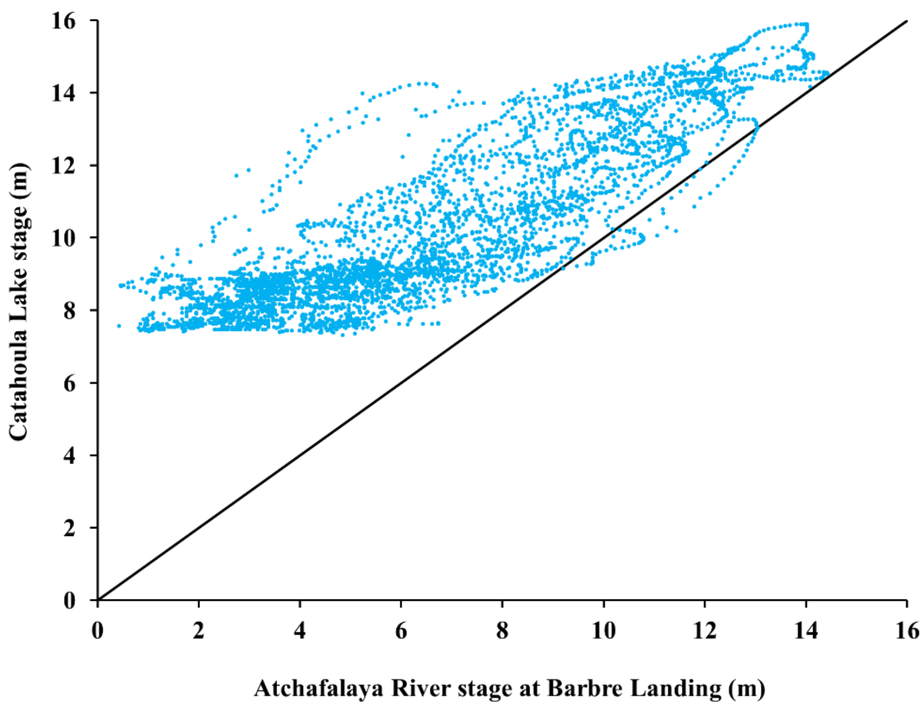


Figure 5. Relationship between the Atchafalaya River at Barbre Landing and the lake stage for the period 1961-1971 with a 1:1 line defining the lower limits of backwater conditions.

Pre and post Diversion control structure hydrologic investigation

Scaling regimes

Scaling regimes refer to the timescales over which scaling (power-law variance as a function of timescale) holds linearly in a frequency domain, and characterize the time series (Tessier et al. 1996, Newman 2005). Scaling regime is identified from the spectral variance density distribution of a time series and its distribution. Fraedrich and Lardner (1993) found that within a frequency band, the scaling regime defines the characteristic of the time scales of atmospheric dynamics, and other geophysical and ecological time series also are amenable to similar analysis (e.g., Bak et al. 1988, Brown et al. 2002).

We conducted the standard method of spectral analysis for lake stage pre and post Diversion Channel construction, and determined scaling regimes of the obtained spectra. To achieve this analysis, fast Fourier transform (fft) was applied to obtain the power spectrum. Afterward, the scaling regimes were identified as timescales over which the scaling holds linearly:

$$\frac{\log(x)}{\log(y)} = -\frac{m}{f}, \qquad (6)$$

where f is the frequency, $\log(y)$ is the logarithm of the power spectrum, and $\log(x)$ is the logarithm of the frequency, and m the slope.

Estimation of the effect of the Atchafalaya River incision on the lake

We used data from the Atchafalaya River at Barbre Landing for 1880 to present to estimate incision of the upper Atchfalaya River and its effect on the lake stage for the period 1961-1972. We determined the trendline of the time series of data, and we obtained the slope of the line to determine the rate at which the Atchafalaya River had lowered from 1880 to 1972. To estimate the effect of incision on Catahoula Lake via changes in the backwater effect, we created a synthetic dataset of Barbre's Landing from the 1960s, corrected for incision by simply adding this number to the river level. Then, we estimated the lake stage for this estimate of unincised condition of the Atchafalaya River using eq. 5.

Lake Depth-Duration-Curves

Depth-duration-frequency curves depict the water depth as a function of duration for given return periods and are important to understand hydrologic regime of waterbodies (Overeem et al. 2008). We constructed depth duration curves of the lake for the pre- and-post-Diversion Channel periods, and for the estimated lake stage as if the Atchafalaya River was unincised. We also compared depth-duration-frequency curves among time periods. Note that there was a difference in the gauge. For the period of 1960s, data from Placid Oil Co. gauge was used, while data from the gauge at the center of the lake was used for the post-Diversion Channel period. For the post-Diversion Channel period, data from 1974 to present were used because one of the biggest flood event of the century in the LMAV occurred in 1973 (Noble and Murphy 1975), which could skew results of comparisons among periods.

Stochastic model

We developed a stochastic model of lake hydrology, which involves a deterministic part and a probabilistic part (Taylor and Karlin 1984). The deterministic part was the downstream control of the Atchafalaya River at Barbre Landing on the lake as gradient (∇_I, eq. 5), and the probabilistic part was all other sources of variation such as precipitation and exchange between the lake and unmeasured storages. We used a set of random variables constrained by historical time series for the 1961-1972 period.

Stochastic Model of the Lake

The stochastic model of the lake is written as:

$$\mathrm{CL_i} = \mathrm{BL_i} + \mathrm{G_i}\ , \tag{7}$$

where $\mathrm{CL_i}$ is the water stage of the lake at time i (day); $\mathrm{BL_i}$ is the water stage of the Atchafalaya River at Barbre Landing at time i (day) (deterministic); and $\mathrm{G_i}$ is the modeled gradient from the lake to Barbre Landing at time i (day) (stochastic).

ARIMA Model

The autoregressive integrated moving average (ARIMA) model is a generalization of an autoregressive moving average (ARMA) model. ARIMA is applied in cases where data are non-stationary, and where time lag can be applied to remove the non-stationarity (Box and Jenkins 1970). We used SAS to determine the correct order of ARIMA (p, d, q) in which p is the number of autoregressive terms, d is the number of differences needed to confer stationarity, and q is the number of moving average terms:

$$\widehat{\mathrm{G}}_t = \mu + \underbrace{\textstyle\sum_{i=1}^{p} \emptyset_i \left(\widehat{\mathrm{G}}_{t-i} - \mu\right) + \varepsilon_t}_{\mathrm{AR}} - \underbrace{\textstyle\sum_{i=1}^{q} \theta_i\, \varepsilon_{t-i}}_{\mathrm{MA}}\ , \tag{8}$$

where $\widehat{\mathrm{G}}_t$ is the gradient difference, $\emptyset_i$ and θ_i are fitted parameters of the model for the period 1961-1971, μ is the mean of G, ε_t the residual obtained from the difference between gradient difference (G') values of the day after subtracted to the day before, t the day, and ε_{t-i} is a random shock occurring i days prior to day t. We used SAS to identify the best values of p and q using Akaike (1974) information criterion (aic) and the autocorrelation (ACF) and partial autocorrelation (PACF) of Ghat. We computed the variance σ_{ε}^{2} of shocks of the residual ε_t needed to compute the moving average (MA) equation because

$$\varepsilon_t \sim N(0, \sigma_{\varepsilon}^{2}) . \qquad (9)$$

Multivariate model of lake storage

We developed a multiple linear regression model for the lake storage variation (ΔS_i), which consisted of the difference between the lake stage (CL_i) and the Black River at Jonesville stage as a gradient ($\nabla_{(CL\text{-}Jvl)}$), and the Little River inflows (IF_i) to the lake. The multiple linear regression model of the lake storage variation (ΔS_i) is written:

$$\Delta S_{\,i} = \alpha_1 + \alpha_2 \nabla_{(CL-Jvl)} + \alpha_3 IF_i , \qquad (10)$$

with $\Delta S_{\,i}\, Model$ the model of the lake storage variation, α_1, α_2, and α_3 are fitted parameters of the model for the period 1961-1971. We used SAS to identify the best fitted parameters, the p-value, and R^2 of the model.

RESULTS

Hydrologic influences of Little River

Lake level changes depended on more parameters than the flow received from its watershed. There was no strong relationship between the Little River watershed influx and lake storage changes (Fig. 6).

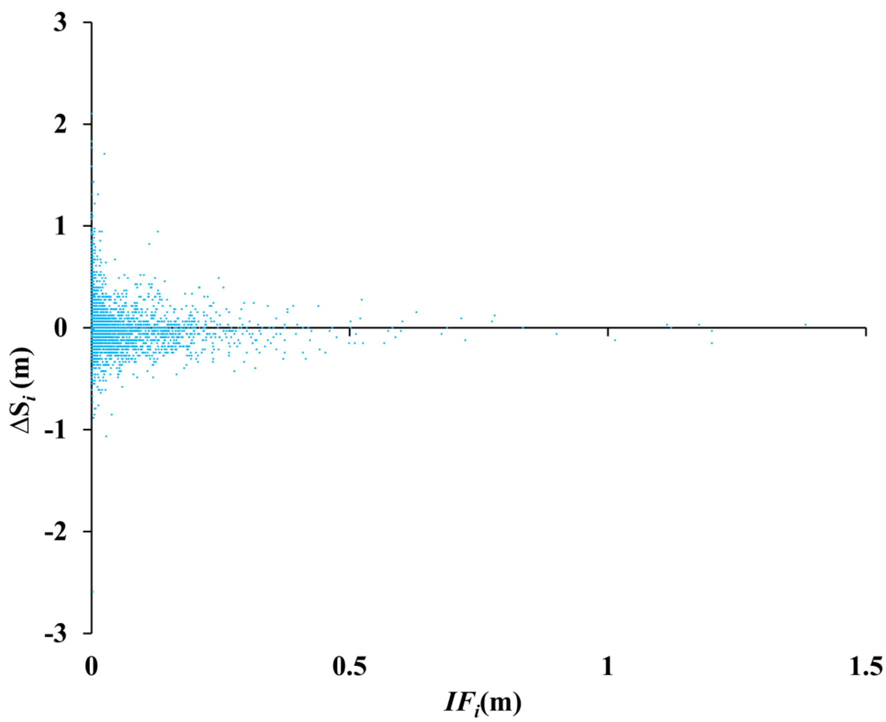


Figure 6. Relationship between the change in storage ($\Delta \mathbf{S_i}$) of Catahoula Lake and the Little River flow ($\mathbf{IF_i}$) entering the lake for the period 1961-1971.

Hydrologic influences of Tensas-Ouachita-Black rivers

The outflow gradient to Black River was not simply related to changes in lake storage (ΔS_i) (Fig. 7). It is clear that the lake changes are not a simple function of the hydrologic influences of the Black and its constituent rivers such as Tensas and Ouachita rivers.

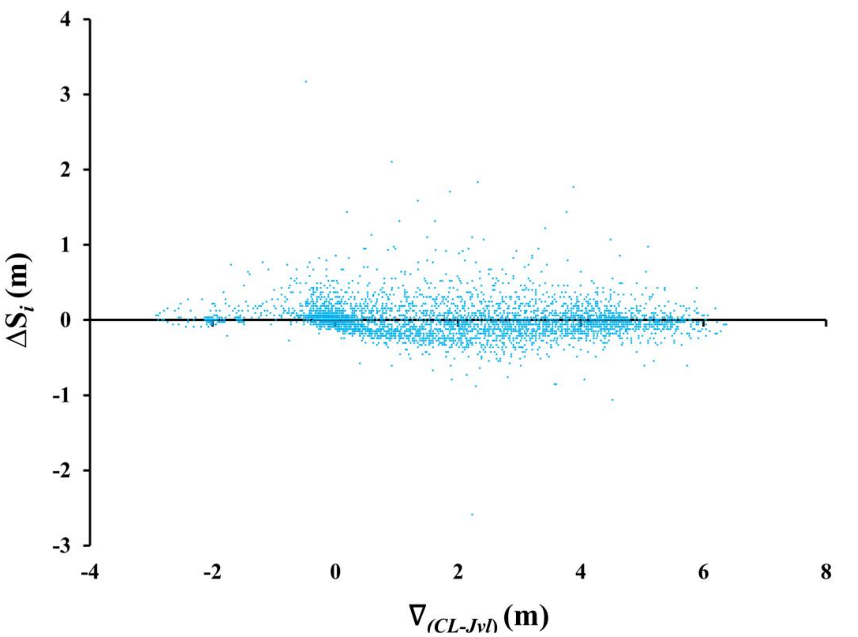


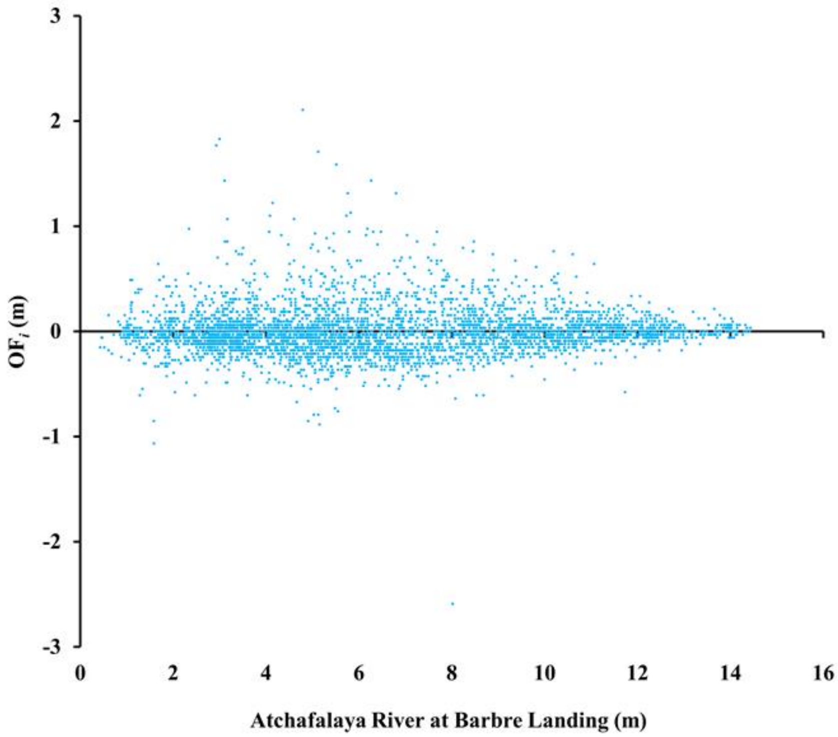
Figure 7. Relationship between the difference of daily lake stage (CL_i) and daily Black River stage at Jonesville ($\nabla_{(CL\text{-}Jvl)}$) and the daily change in lake storage (ΔS_i) for the period 1961-1971.

Hydrologic influences of the Atchafalaya-Red-Mississippi rivers

Our substantial analysis of the time series record of the lake water storages did not find any evidence of relationship with Atchafalaya-Red rivers levels except when water level in the rivers is above the lake bottom, 7.3 m (Fig. 8). Below that, variability of water level in the lake is independent of the Atchafalaya-Red rivers, and further not a function of the Mississippi River regime. However, the lake stage is controlled greatly by the Atchafalaya River stage (r^2=0.76) when river stage is greater than 7.3 m (Fig. 5).

At the river stage higher than 7.3 m, the lake stage indicated dependency on the Atchafalaya-Red rivers downstream. The variance of the lake levels was higher when the river level is higher because generally the region is wetter and the backwater effects are strongest. The variability of the Atchafalaya River levels dictated the hydrologic behavior of the lake by backwater because peaks in the time series of the river and lake occurred simultaneously (Fig. 9).

A



B

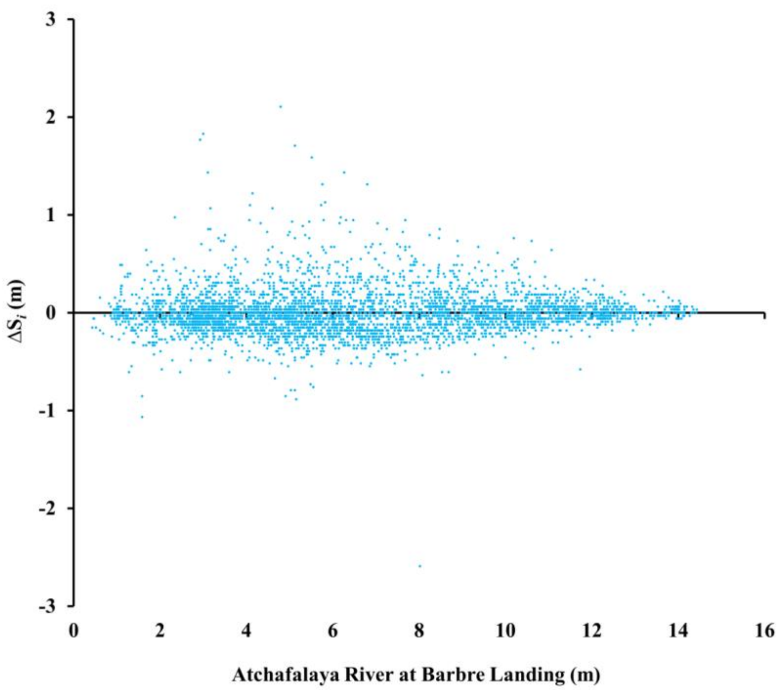


Figure 8. Relationship between the stage downstream at Atchafalaya River at Barbre Landing and (A) the net out flow ($\mathbf{OF_i}$) of the lake, and (B) the daily change in lake storage ($\Delta\mathbf{S_i}$) for the period 1961-1971.

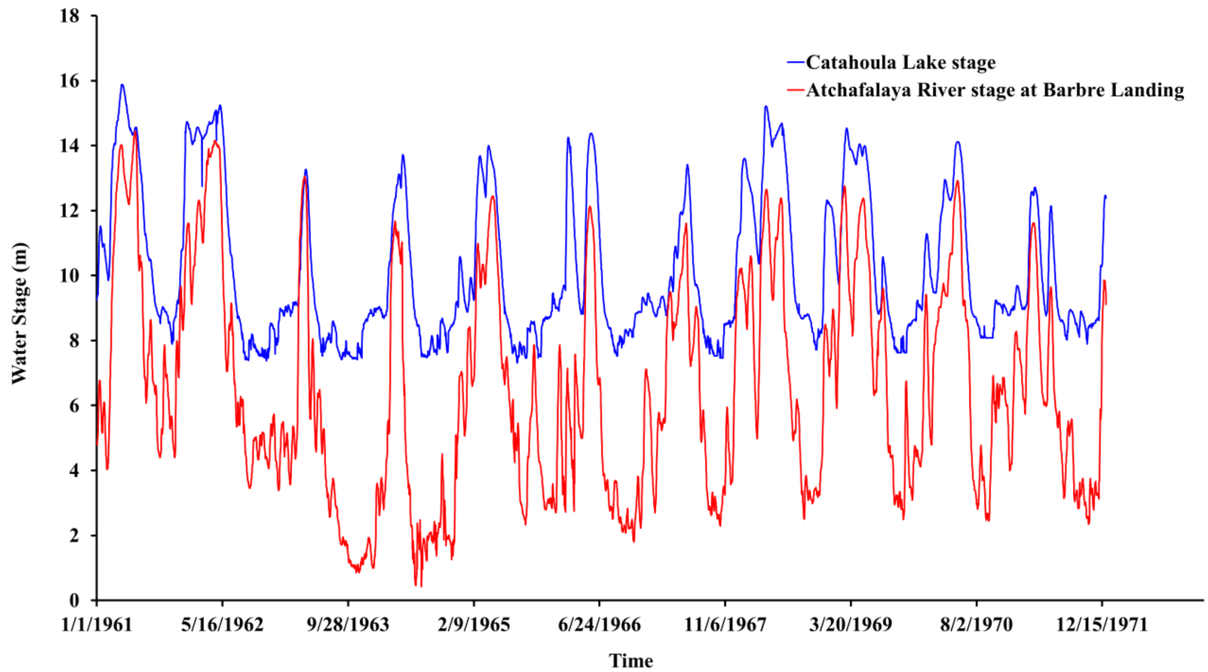


Figure 9. Simple relationship between the Atchafalaya River at Barbre Landing and the lake stage for the time series period 1961-1971.

Historical hydrologic regime of the lake

The power spectral analysis identifies a peak for both pre and post- Diversion Channel construction at the annual time scale (Fig. 10). The lake levels during the pre- and post-Diversion Channel period show a first break in the slope on a running period that corresponds to 3 months, and a second break that corresponds to 7 days while the slopes for these 3 distinct scaling regimes are completely different from each other. For the pre-Diversion Channel period; we observed respectively a slope of $m_1 = -0.47$, $m_2 = -1.60$, and $m_3 = -0.72$, and for the post-Diversion Channel period $m_1 = -0.44$, $m_2 = -1.75$, and $m_3 = -0.67$. The hydrologic behavior of the lake prior to the Diversion Channel construction is likely different from that of the period of management of the lake using the Diversion Channel. The slopes of the first and third timescales during the pre-Diversion Channel period are less than that of the post-Diversion Channel while the slope of the second timescales of the pre-Diversion Channel period is higher than that of the post-Diversion Channel period. The biggest difference between periods is the 7 day – 3 month scaling regime, in which the variance was much less at the higher frequencies in the Diversion Channel period as compared to prior to the Diversion Channel.

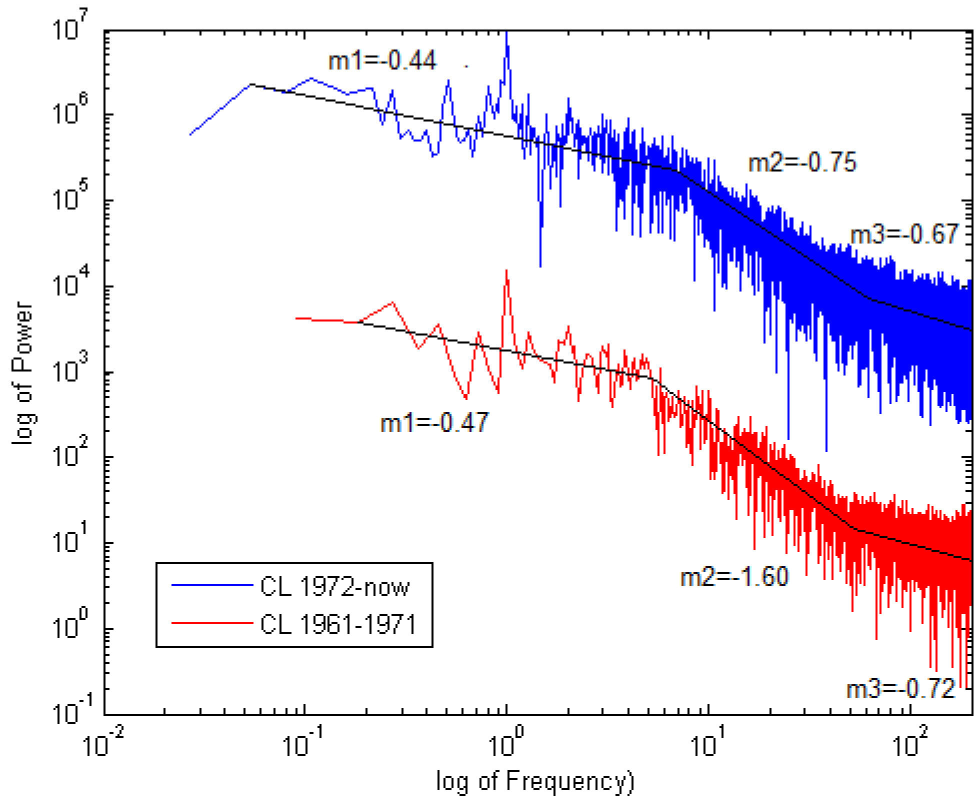


Figure 10. Power spectrum analysis of the time series of the lake level for the pre-diversion canal period (below) and the post-diversion canal period (above) with observed breaks in the slopes of the power spectrum.

Estimation of the effect of incision of the Atchafalaya River on Catahoula Lake

The long-term trend in stage on the Atchafalaya River at Barbre Landing was -0.0107 m per year (Fig. 11). That means that the river was, on average, 1.0 m higher in 1880 (before incision) as compared to 1971 when the Diversion Channel was constructed, with attendant effects on backwater to Catahoula Lake.

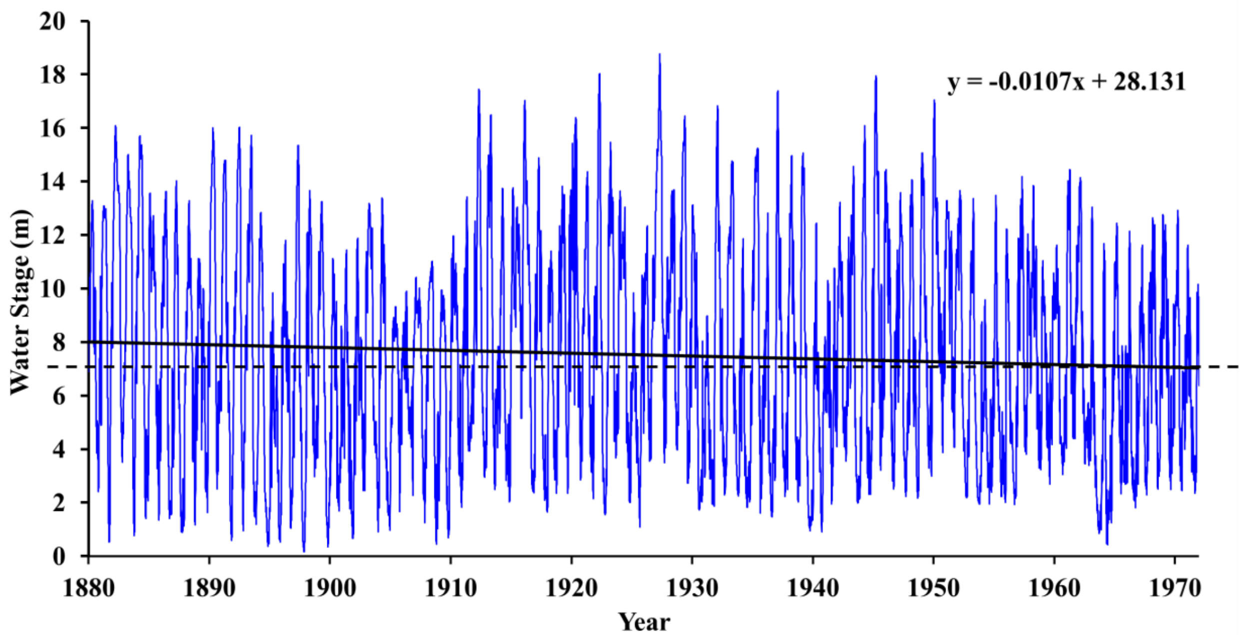


Figure 11. Long-term trend in stage on the Atchafalaya River incision at Barbre Landing for the 1880-1972 period. The dashed line indicates 7.3 m, which is the elevation of the bed of Catahoula Lake.

Incision of the Atchafalaya River has likely decreased the frequency of the backwater effect on Catahoula Lake. There were 207 days per year of backwater effects (stage >7.3 m) in 1880, but by 2010 it was only 120 days per year (Fig. 12). Thus, the changes in regional hydrology have decreased the frequency of backwater effects on the lake by about 42% on average. Individual years have had more extreme behavior. For example, in 2006, there were only about 13 days without backwater effects. The duration of backwater effects are not strongly related to large events. For example the floods of 1927 (n=175), 1945 (n=165), 1973 (n=150), and 2011(n=120) did not all produce unusually long periods of backwater.

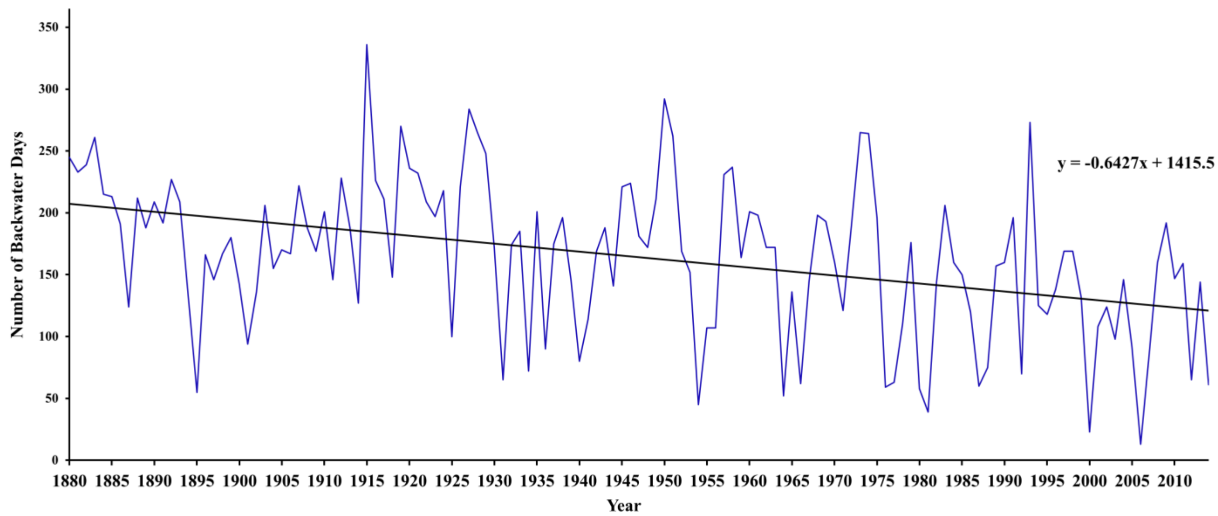


Figure 12. Estimation of the expected number of backwater days per year for 1880 to present period, and the trendline used to compute the number of backwater days.

Had the Atchafalaya River not incised from its 1880 condition, the modeled effect on Catahoula Lake stage in the 1960s was increased stage during high-water, backwater events (Fig. 13). The mean estimated increase in stage at the peak of the annual flood was 1 m, corresponding to the 1 m of incision. The duration of differences between simulated stage from an unincised Atchafalaya River and the actual stages was 2-46 days per year (Fig. 13). Therefore, there would probably be 2-46 days per year more in backwater flooding than in an unincised condition.

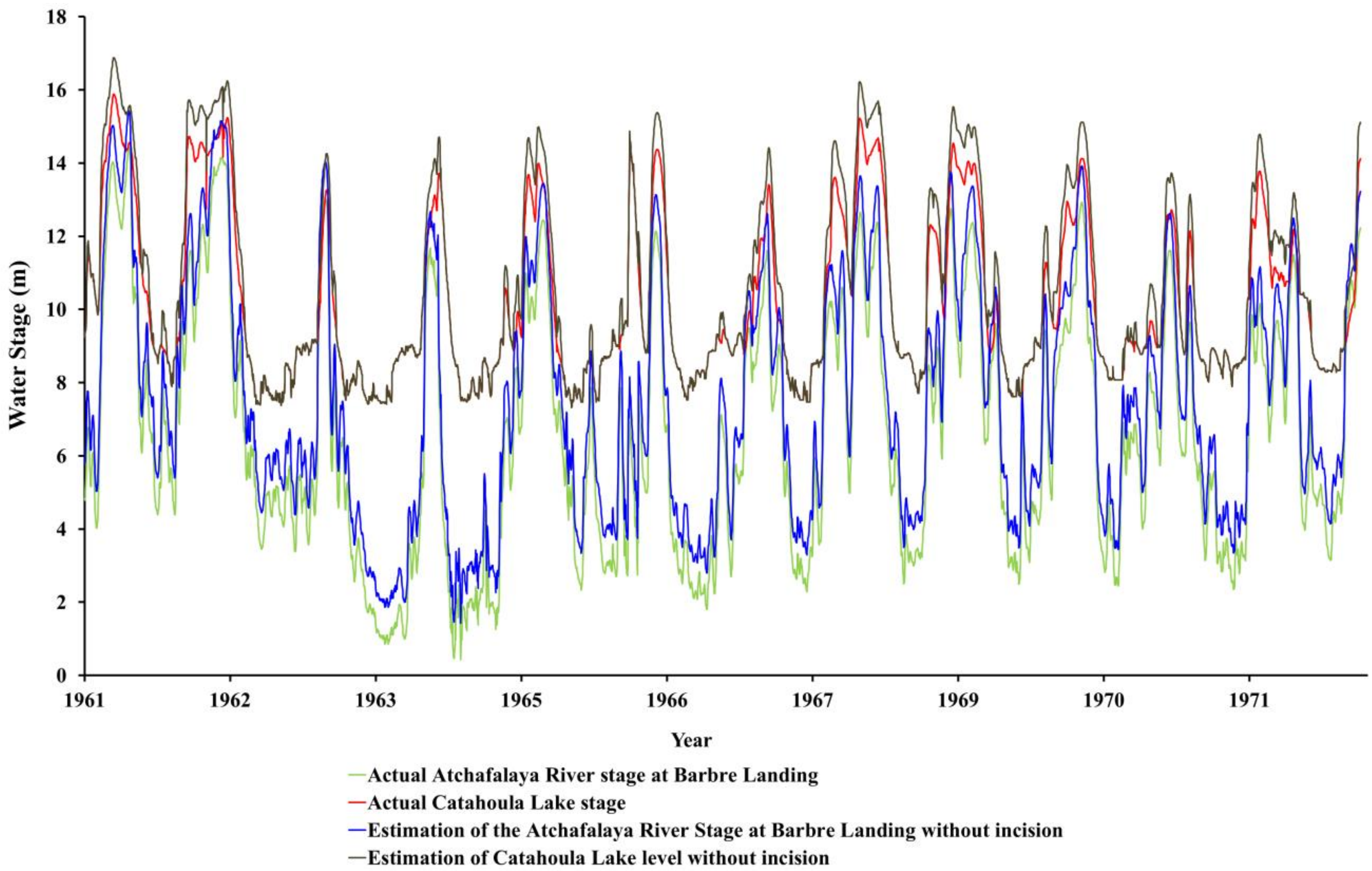


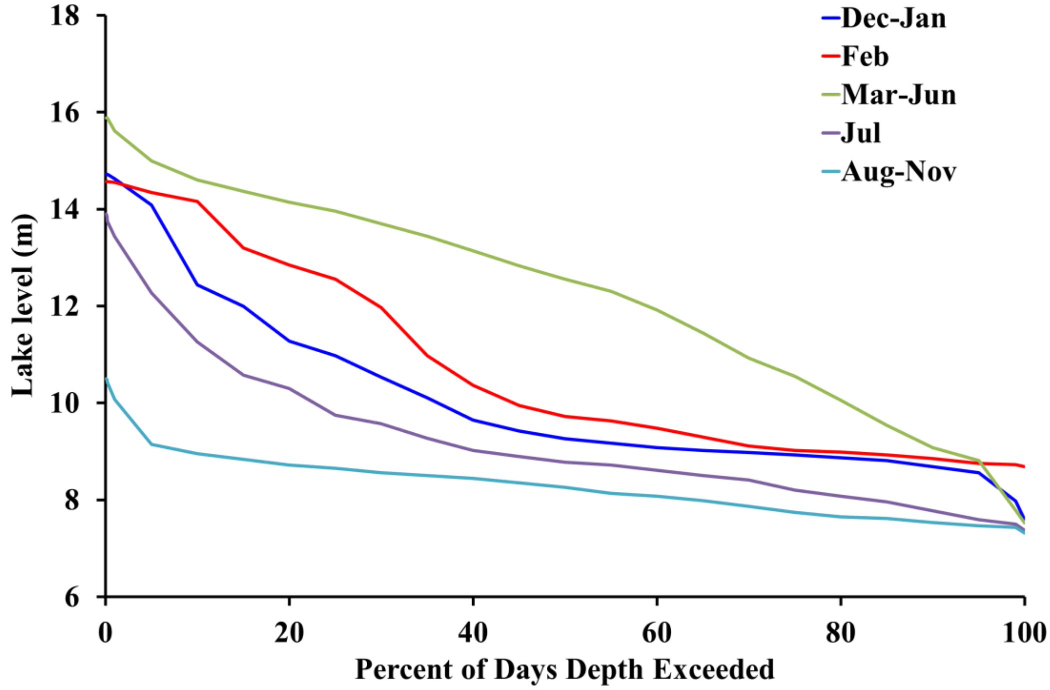
Figure 13. Estimation of lake stage in the absence of the Atchafalaya River incision from 1880 through 1972

Depth-duration-curves of the historical regime of the lake

The pre- Diversion Channel depth duration curve of the lake (Fig. 14A) showed that August-November were months of low water; thus, the chance that the stage would exceed 10 m was low, and the chance of lake levels lower than 7.5 m was high. March-June were months of high water but rarely higher than 15 m, and always greater than 8.5 m. July, December, January, and February were transition months where the water levels exceeded 9-10 m about half the time. There was a relatively strong distinction between dry and wet periods for middle-exceedance events (i.e., the depth-duration line is sloped throughout the middle portion).

With the management of the lake according to the Diversion Channel, the water levels were different (Fig. 14B). The biggest change is that spring (March-June) lack very dry periods but are generally up to 1 m lower for middle-probability events. August-November are still the low-water months, but the lack of variability during middle-exceedance events meant that dry periods are now not as dry as prior to the structure, and these dry months now experience rare, high-water events (up to 14 m) that did not occur in the 1960s. The water level during February is now up to 1-2 m higher during common and middle-probability events (Fig. 16). July, December, and January are still transition months, with the greatest range in possible stages, and an increase up to nearly 1.0 m for December and January during middle-probability events. Note that very low events were likely related to the differences in the gauges in the two periods.

A. Pre-Diversion Channel



B. Post-Diversion Channel

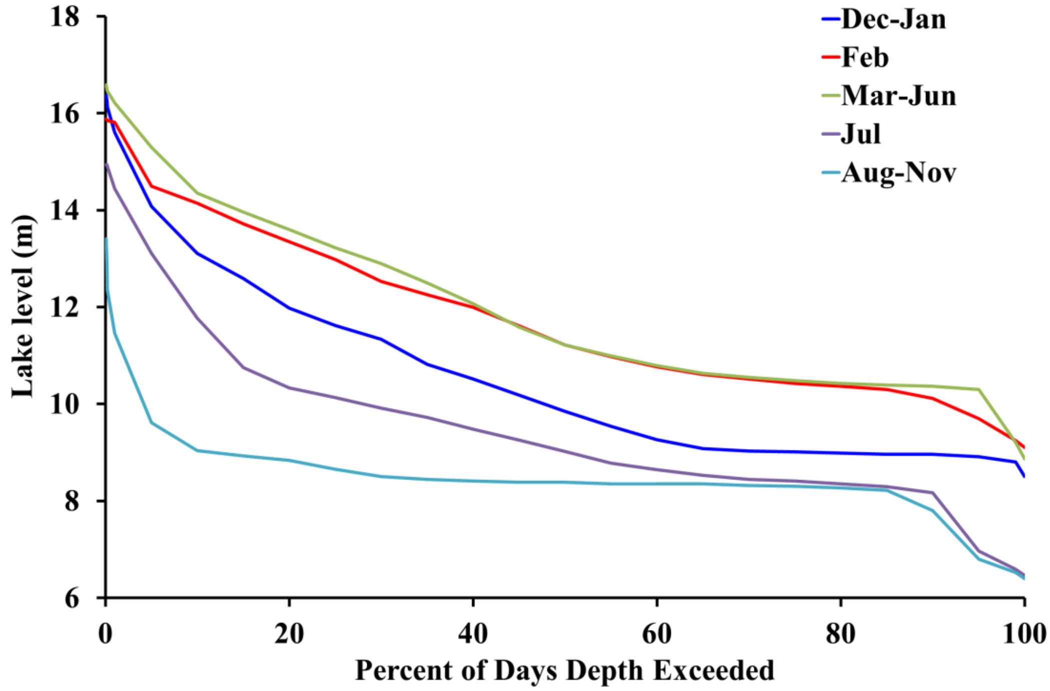


Figure 14. Seasonal depth duration curves for the pre-Diversion Channel period (A) and for the post-Diversion Channel period (B).

Our model of the effects of incision of the Atchafalaya River on Catahoula Lake indicated similar depth-duration regimes but generally higher water prior to incision (Figs. 14, 15, 17). During rare events the modeled water level was higher after incision by up to 1.0 m (Fig. 18). During high-water months in the spring (when backwater was common) in the 1960s, the modeled effect of incision was simply to lower the water by 1 m during common and middle-probability events (Fig. 18). Bigger differences were found for months when backwater effect was more ubiquitous during this period; backwater flooding would have been more common in the absence of incision (i.e., March-June) (Fig. 18). The modeled effect of incision on water levels in dry times was virtually zero because backwater conditions are rare at those times.

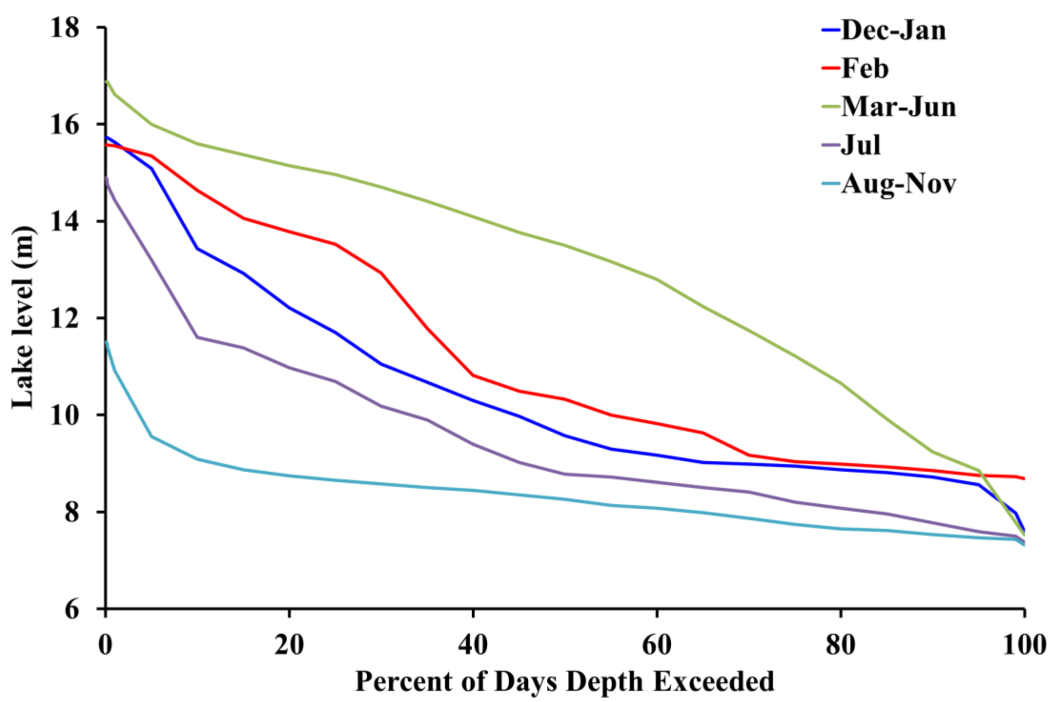


Figure 15. Seasonal depth-duration-curves of the estimated lake level without incision prior to the Diversion Channel construction.

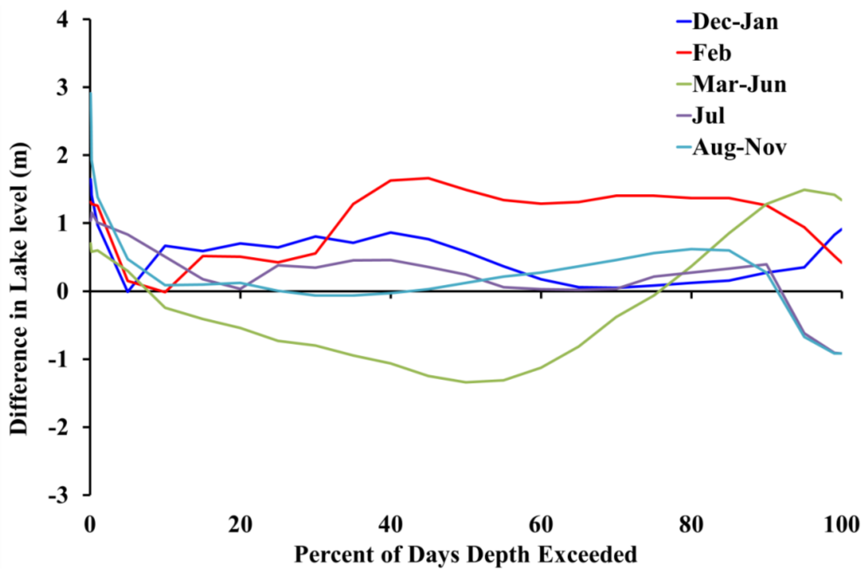


Figure 16. Differences in seasonal depth-duration curves to quantify effect of the Diversion Channel (Fig. 14B minus Fig. 14A).

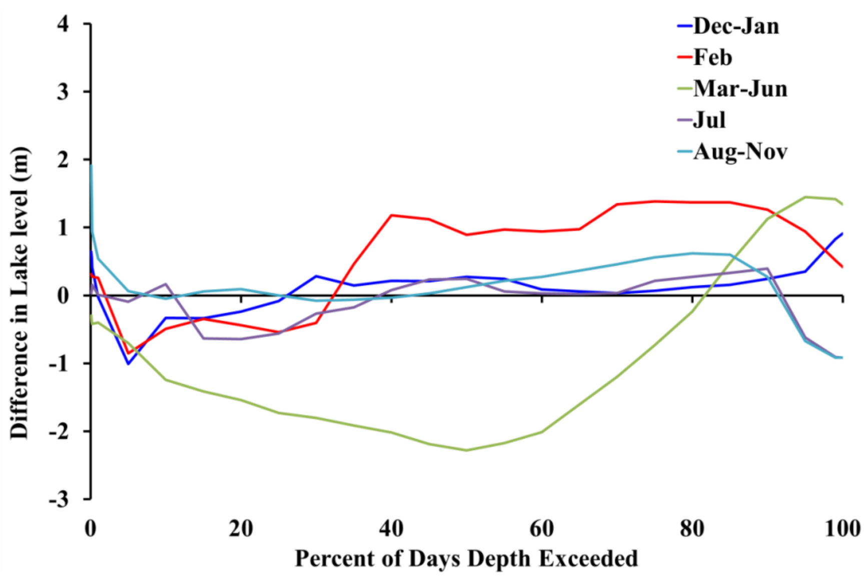


Figure 17. Differences in monthly depth-duration curves to quantify effect of the Diversion Channel and incision of the Atchafalaya River (Fig. 14B minus Fig. 15).

Net modeled changes in the lake during 1880 to present

The net modeled effects of incision and operation of the Diversion Channel on water levels are complex. During wet months in the spring, the Diversion Channel operation is generally keeping lower water than prior to its construction. However, the post-Diversion Channel regime still generally (middle frequencies) retains lower water in the spring than the modeled pre-incision conditions (Fig. 17). The net effect of water control and incision on low water events is dominated by the water control structure because incision does not affect low-water conditions.

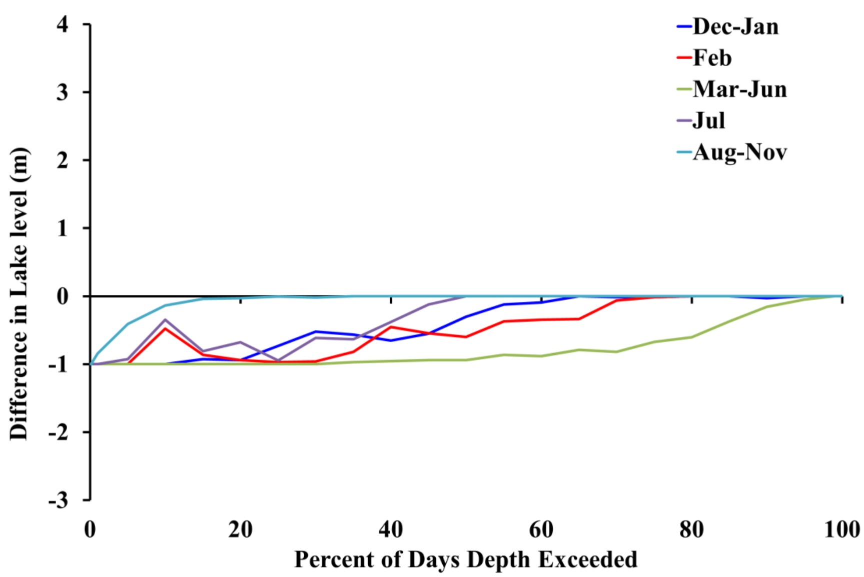


Figure 18. Differences in seasonal depth-duration curves to quantify the effect of the incision of the Atchafalaya River (Fig. 14A minus Fig. 15).

Stochastic model of the lake

Best-fit coefficients of the ARIMA (2, 0, 4) are respectively $\emptyset_1 = -0.44182$,$\emptyset_2 = -0.20988$, $\theta_1 = -0.10242$, $\theta_2 = -0.0051$, $\theta_3 = 0.02783$, and $\theta_4 = 0.05268$. Unfortunately this ARIMA (2, 0, 4) model is insufficient to represent the model properly because there is not a great difference in the variation of the data when we add shocks. Shocks do not sufficiently increase the variation of the data (Figs. 20 and 21).

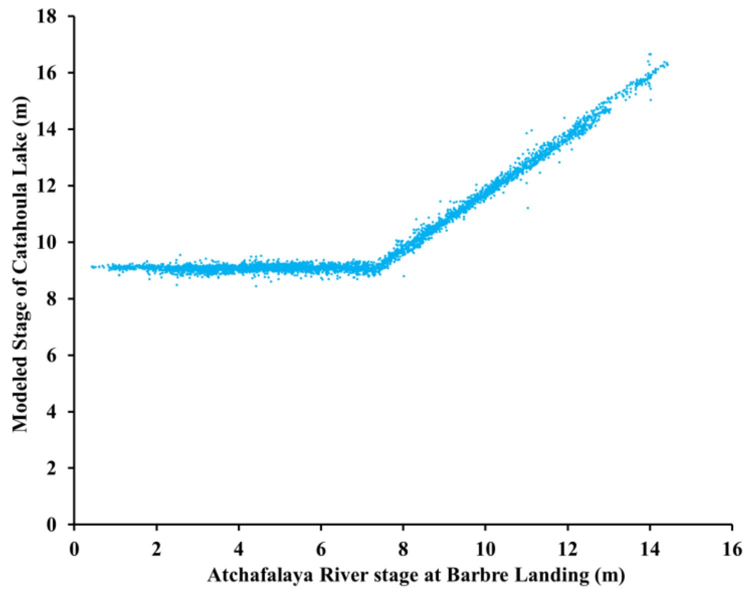


Figure 19. Relationship between the resultant stochastic model of lake level and stage of the Atchafalaya River at Barbre Landing (compare to figure 5).

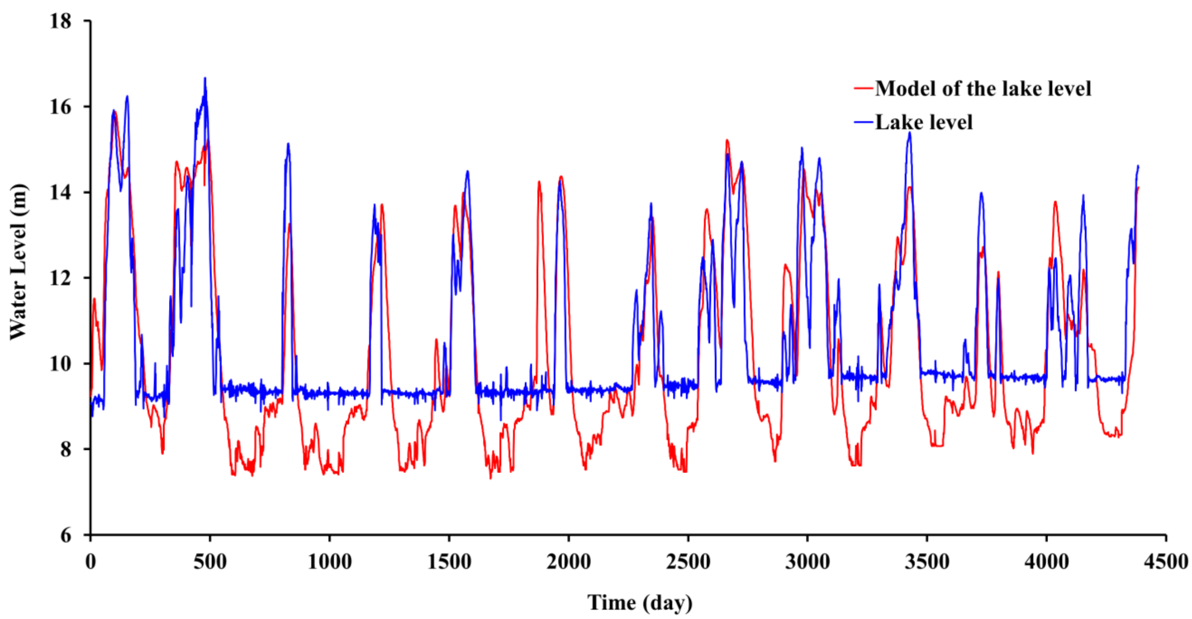


Figure 20. The stochastic model of lake level.

Multivariate model of lake storage

As a result, the coefficients of the model are respectively $\alpha = 0.01610$, $\emptyset = -0.00389$, and $\beta = -0.17639$. The model was statistically significant with p-value<0.0001, but it did not capture much of the variations in lake level (r^2=0.0061). This model was not sufficient to properly represent the lake storage variation (ΔS_i) (Fig. 21).

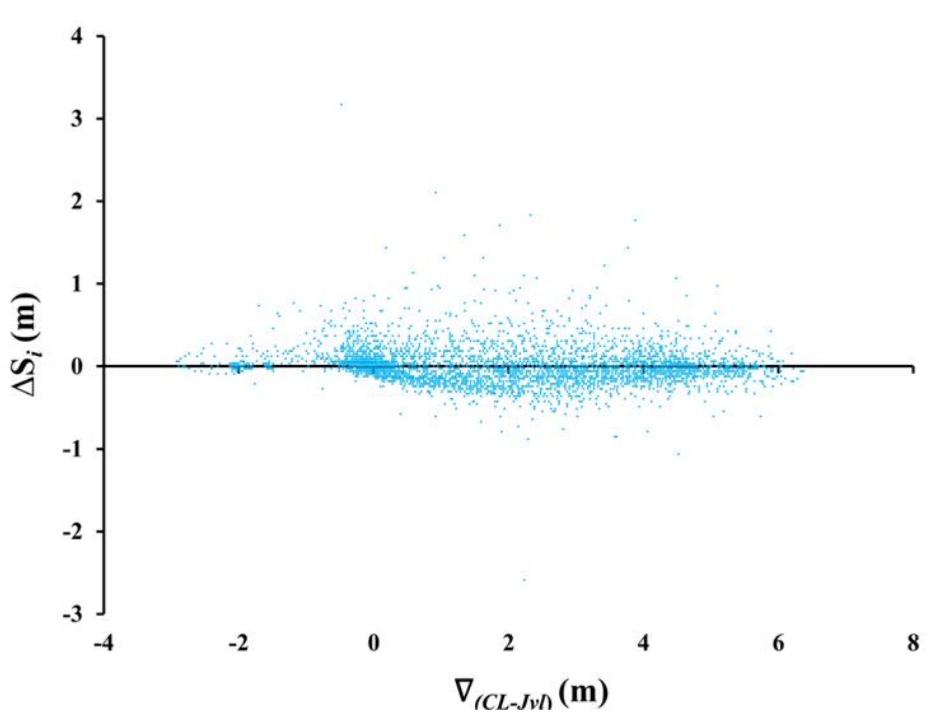


Figure 21. Relationship between the difference of lake stage and the Black River stage at Jonesville as a gradient ($\nabla_{(CL\text{-}Jvl)}$)and (A) the net out flow ($\mathbf{OF_i}$) of the lake, and (B) the daily change in lake storage ($\Delta\mathbf{S_i}$) for the period 1961-1971

DISCUSSION

The hydrologic regime of the lake is function of the Red and Mississippi rivers while the LMAV is wet. The series of modifications in the LMAV involve regime change within the river. For the period 1961-1962 the highest water level recorded within the Atchafalaya River at Barbre Landing was around 14.5 m while for the period 1963-1971 the highest water level recorded was around 13 m. These variations imposes changes in the hydrologic regime of the lake in which the highest lake water levels observed during the period 1961-1962 was about 16 m, for the period 1963-1967 about 14 m, for the period 1968-1969 about 15 m, and for the period 1970-1971 about 13 m, while a drastic drop is observed when the river drops. The obvious river levels drops recorded in the time series of the Atchafalaya-Red rivers are due to geomorphologic incisions of the rivers which are the results of the hydrologic modifications of the LMAV (Aslan et al. 2006).

Differences in hydrologic regime in Catahoula

The basal (~100 years ago) sediment source in Catahoula Lake was less acidic and related to Mississippi River alluvial sediment (Latuso 2014). The results of simulating effects of hydrologic change in the LMAV indicated less backwater flooding, which is consistent with a lack of connectivity to the lake and a loss of sediment deposition Previously during flooding, which lasted longer than prior to the 1970s, the lake connected to large rivers more often than during the post-hydrologic modification period (1972-).The intensive construction of locks and dams on the Mississippi, Red, and Black rivers has apparently disconnected the lake from sediment-bearing flows from the Mississippi River to those originating in upland and adjacent coastal plain through Little River.

All of that in turn may possibly affect the lake ecology, and may have contributed to vegetative community composition changes.

Changes in low-water variability caused by the Diversion Channel are consistent with the results of Bruser (1995), who suggested the increase in woody vegetation may result from the decrease in variability of the lake stages after the management of the lake by the Diversion Channel.

Overall, modifications in the regime of the lake are observed, and the Diversion Channel seems to not completely fulfill its primary purpose to mimic the natural regime of the lake. However, a more advanced study using longest historical time series of the lake based on the hydrologic influence of the Atchafalaya River on the lake would be useful, and the climatic effects of the teleconnections on the Mississippi River basin can also be used to further estimate longer term variation. The hydrologic subsurface and surface interconnections with other lakes such as Little Lake and other influxes from apparent non-significant watersheds should be taken into account besides the hydrologic influences of major surrounding rivers.

A wide range of natural and anthropogenic stressors influence floodplain lake ecosystems, and might provoke ecological issues including pollution of water due to excessive nutrient inputs, invasion by non-native species, and alterations in the physical characteristics of the floodplain lakes (Leira and Cantonati 2008). Water-level fluctuations affect the biological communities and promote colonization of the lake by other vegetation types, and shifts in the biological productivity of the lake. On the physical environment of the lake, Loiselle et al. (2005) mentioned that lake level changes affect light penetration into the lake, and cause changes in the benthic algae and macrophyte growth within the lake. The size and the distribution of vegetation types within the lake might result to changes in the magnitude and frequency of water-level fluctuations (Morin and Leclerc 1998). Catahoula Lake regime changes due to intensive hydrologic managements in the LMAV might be one on the most important cause that promote the invasion of woody vegetation within the lake because low-water favor re-establishment of emergent species while high water eliminate most of emergent species (Hofmann et al. 2008).

Reduced variability in the dry period

Bruser (1995) reported that in the months of low water (August-October) the variation of lake stage was greater for the pre-Diversion Channel than it was after the Diversion Channel construction (1974-1995). This lack of variance is the result of the anthropogenic management of the lake via the Diversion Channel because the Diversion Channel design is different from that of the original outlet of the lake (French Fork) and may allow the lakebed to dry more rapidly. This study also found this variability exists: The slope of the depth-duration frequency curves in the dry period (August-November) for the pre-Diversion Channel construction is greater than that of the post-Diversion Channel construction. The slope of that same line in the post-Diversion Channel period is flatter and indicates more stability during dry period. However,

Other parameters possibly influencing the lake stage changes

Some variation in lake stages is related to difficulty measuring stage on a large lake affected by seche effects. For example, it is difficult to understand why the lake stage does not relate simply to the water influxes from the Little River watershed. The Dry River in the north end of the lake is probably connected to the Little River (Willis 2009) may have hydrologic influence on the lake that can serve as either a way of gaining or losing water for the lake. Catahoula Lake is a large complex lake with multiple storage locations nearby. Edwards et al. (2014) found the seiche effects on the lake due to the exposure of the lake to water waves, which constitute an important aspect in the management of lakes. The lake orientation related to dominant winds dissipates wave energy significantly. Little Lake a 9.7-km^2 lake approximately 5.6 km northeast of Catahoula Lake has indirect interconnections with Catahoula Lake, and small watersheds such as Hemphill Creek water, Devils Creek in the north, and Flagon Bayou in the southwest of the lake may hydrologically contribute the lake water stage although their contribution to the lake may be minor and occasional.

Importance of Groundwater in Catahoula Lake

The results of the depth-duration frequency analyses show that, during dry periods, the lake level goes nearly dry; that indicates that the lake is not dominated by groundwater. However, streams within the Little River watershed derive base flow from groundwater (Gaydos et al. 1973). Fisk (1940) reported that terrace deposits and alluvial deposits in most parts of the watershed are the major sources of groundwater. Together, these indicate inflow to the lake is partly related to the abundance of groundwater supply to the Little River in dry periods. The existence of seeps on the northwest side of the lake also supply the lake with water and affect vegetation on the lake margins (Brown 1943) but probably do not play a key role in the lake stage variation.

The groundwater contribution to Catahoula Lake is low relative to some floodplain lakes globally. For Tonle Sap Lake in the Mekong River floodplain, the hydrologic budget is dominated by rainfall, evaporation, and overland flow of large rivers (Kummu et al., 2014), while for Lago Grande de Curuai in the Amazon River floodplain water from rainfall, evaporation, groundwater, runoff from the upland local watershed, and bank-seepage are the major components of the water budget of the lake, but seepage from and into the groundwater system is highly variable (Bonnet et al. 2008).

Effects of Cleaning of Big Raft and Red River rafts on regional hydrology

Prior to 1880s, major log jams or “rafts” on Red and Atchafalaya rivers constituted a major obstacle for navigation while playing an important role in avulsions (Phillips and Park 2009), and at that time the Atchafalaya River carried nearly 3% of the flow of the Mississippi River downstream. In the 1800s the Atchafalaya River started receiving more downstream water from the Mississippi River. Both the removal of the Red River log jam in between 1833 and 1870s and the removal of Atchafalaya River log jam in between 1839 and1855 increased the importance of the Atchafalaya River downstream flow (Reuss 2004; Mossa 2013). The removal of rafts has to some extent modified the hydrologic conditions of the LMAV. Fisk (1952) reported that the Atchafalaya River began to enlarge and carry a higher percent of the Mississippi River shortly after the removal of log jams through the Red and Atchafalaya rivers because its course had greatly been shortened and steepened to the Gulf of Mexico. The removal of those rafts and may have promoted the incision of the Atchafalaya River because the sediment transport may have increased as the gradient became steeper. Also, this channel was directly modified to increase flow and ease navigation (Reuss 2004). Thus, indirectly, the increasing of flow through the Atchafalaya River may have reduced the number of days of backwater effects in the LMAV and on the lake.

Context of Catahoula Lake in the managed floodplain

Rivers provide a wide range of services for humans by providing water for agricultural, industrial, and ecological purposes including routes for navigation, sites for recreation and spiritual activities (Hudson et al. 2008; Gao 2009). However, many great rivers around the world have been altered to provide societal benefits but these changes are detrimental to many valuable ecosystem services, and threaten freshwater biodiversity by changing natural water regime

(Arthington et al. 2006). The floodplain of the Mississippi River is the result of intensive hydrologic alterations that influence waterbodies in the LMAV. Hudson et al. (2008) found alterations of the LMAV caused fundamental fluvial process changes that have geomorphic consequence on both rivers and floodplains. He found that this case is true for other rivers such as Rhine River in Netherland that presents similar configuration with the Lower Mississippi River, and found that flood management is highly correlated to floodplain geomorphology. New backswamp lakes are created and hydrologic alteration of impounded floodplains have occurred due to floodplain geomorphic changes within embanked floodplain and meander bend cutoffs for river channel adjustments. That involves the hydrologic context of Catahoula Lake depends on the intensive alteration of the LMAV and relates to the Mississippi River, and may be the cause of vegetation shifts within the lake.

Comparison with other floodplain lakes

Considering the hydrologic characteristic of floodplains lakes, we compare the water budget of the lake to other floodplain lakes located in almost similar geomorphologic conditions. Lake Lago Grande de Curuaí, in the floodplain of the Amazon River in Brasila, is 33 times larger than Catahoula Lake when flooded (Bonnet et al. 2008). Lago Grande de Curuaí gains most of its water from the Amazon River. During the rising period, rainfall on the lake surface area and runoff prevent river water from entering the lake while water loss is mainly governed by evaporation and seepage into ground water. The water level fluctuation of this lake ranges from 3.03 m to 9.61 m while that of the Catahoula Lake ranges from around 2.7 - 6 m. The rising phase of the floodplain begins between November and January and lasts until May-June while its receding phase occurs from July to November.

Another case is the Lake Calado in the central Amazon basin. This lake is connected to the Solimões River year-round and its rise and fall is a function of a combined hydrologic influence of local runoff accumulation and river flooding, and the permanent area of the lake that contains water is around 2 km^2 while the greatest flooded area is around 8 km^2. Its watershed is about one hundred times smaller than that of Catahoula Lake. 57% of the total influxes to this lake is from runoff and 21% river water inflow during a year, and loses water from seepage and evaporation (Lesack and Melack 1995). Catahoula Lake receives most of its water from interconnections with surrounding rivers and indicates complex hydrologic links to nearby waterbodies while its water level is poorly related to the amount of water that enters the lake via its watershed. All of that can be explained by the variability of the lake to the ways the lake gains water. However, no intensive modifications were observed in the Amazon River floodplains cases cited above.

Other floodplain lakes in the world experience hydrologic effects of their surrounding rivers. Tonle Sap Lake of Cambodia, one of the largest freshwater bodies in Southeast Asia, located in the floodplain of the Mekong River, is a productive ecosystem that is a natural storage for the lower Mekong basin (Rainboth 1996; Kummu et al. 2014). This lake is a floodwater reservoir for the Mekong River system during the dry season (November-April). Kummu and Sarkkula (2008) found that the water stage of this lake is a function of the Mekong mainstream, and the flood pulse of the lake relies on the changes in the Mekong mainstream. Its watershed is about the size of the Mississippi River watershed, and permanently flooded area convers 2400 km^2, about 20 times the size of Catahoula Lake. March, April, May, and June are months of low water with a level of 1.44 m during the driest season and 9.09 m during the flooding period.

A variation of volume of ~1.8 km^3 from the driest season to 58.3 km^3 in Tonle Sap Lake is observed, while a variation of volume of ~0.036 km^3 to 2.16 km^3 is observed for Catahoula Lake, thus a ratio of 1:60 of the volume of the Catahoula Lake and 1:32 for Tonle Sap Lake: both lakes exhibit high hydrologic variability. However, the components of the water balance for Tonle Sap Lake are Mekong River hydrologic influence that counts for more than half of its annual inflow (Kummu et al. 2014). Hydrologic alteration in the Mekong River can directly influence the lake behavior while we have identified that changes in rivers surrounding Catahoula Lake are not the only hydrologic parameters affecting the lake directly.

Woody plant invasion at Catahoula Lake

The vegetative changes in Catahoula Lake to favor woody vegetation over herbaceous vegetation may be related to the hydrological changes observed in this study. Toner and Keddy (1997) reported that river regulation can change the distribution of two main vegetation types: herbaceous and woody vegetation within forested wetlands in humid climates. Often, the alterations of hydrologic conditions result in reduction of flooding in spring and increasing of low water in late summer. The reduction of lake stage fluctuation often causes a succession of herbaceous vegetation to woody vegetation. Depth, duration, time, and frequency of flooding are important parameters that determine the limits of lakebed invasion by woody plants. Also, multiple periods of flooding with short periods between flooding favors herbaceous vegetation because the greater the interflooding period the greater is the chance the lakebed is to be invaded by woody plants. In addition, flooding that lasts longer than 40% of the growing season may prevent the colonization of the wetland-bed from woody plant invasion. Overall, the regulation of rivers can modify the conditions necessary for regeneration and threaten persistent dominance by herbaceous vegetation.

CONCLUSIONS

The understanding of the regime of Catahoula Lake is important because of its strategic placement in the LMAV. Although the Little River watershed constitutes the main upland inflow source to the lake; it is overwhelmed by other hydrologic parameters, including wind and exchanges with nearby rivers and sloughs. Similarly, the effects of the Black-Ouachita-Tensas rivers are complicated related to lake stage Prior to the establishment of locks and dams on the Black-Ouachita-Tensas Rivers, the lake regime might have been more of a function of this complex, but we lack data to investigate this possibility.

The downstream Red-Atchafalaya-Mississippi river system controls a major part of the LMAV and also the lower limit of the lake level when the large rivers are high. The peaks observed in the time series records of the Atchafalaya River correspond to peaks in the lake level via a backwater effect above 7.3 m stage.

Compared to its condition prior to hydrologic alterations, we observe that modifications in the LMAV and the construction of the Diversion Channel have altered the lake regime. Our best estimates is that current lake levels are lower in the high-water spring and less variable in the dry period, and lack the extreme high water events of 100+ years ago.

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